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FIRST QUARTERLY PROGRESS REPORT
PERIOD ENDING SEPTEMBER 30, 1964

# RESEARCH & DEVELOPMENT ON FUEL CELL SYSTEMS

Contract No. NAS 8-2696



Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812



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# RESEARCH AND DEVELOPMENT

# ON

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Under Modification Number 6, Contract NAS 8-2696
For the Period Ending September 30, 1964

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
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Research Division, Department 3341
Allis-Chalmers Manufacturing Company
Milwaukee, Wisconsin

Approved J. L. Platner
J. L. Platner
Program Manager

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# FOREWORD

The first quarterly report, NAS 8-2696-QPR-00001, prepared after Modification Number 6 to Contract NAS 8-2696, was originally issued October 30, 1964. This report, dated January 20, 1965, is a complete and expanded revision of the original report. Technical progress during the period August 1, 1964 through September 30, 1964 is reported.

Work under this contract is being performed by the Research Division of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin. Will Mitchell, Jr., is the Director of Research. Dr. Powell A. Joyner is the General Manager of the Space and Defense Sciences Department of the Research Division. A project type organization was formed to carry out the program specified in the contract. J. L. Platner, Program Manager, has direct responsibility for the management and technical aspects of the program. Program management includes: D. P. Ghere, Assistant Program Manager; Dr. J. R. Hurley, Manager, Systems Research and Development; P. D. Hess, Manager, Engineering; R. E. Lochen, Manager, Fabrication and Testing; C. R. Martin, Manager, Quality Assurance; Gunnar Johnson, Manager, Business Administration; and, M. J. Knuijt, Program Planner.

## SUMMARY

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Because of an early delivery requirement of a 29 volt fuel cell breadboard system to NASA's Manned Spacecraft Center (MSC), Houston, Texas, an all-out effort was directed toward the fabrication and verification test of a 1800 watt, 29 $\pm$ 2 volt, fuel cell breadboard system for delivery to MSC.

An existing 1.5 KW fuel cell breadboard system was dismantled and inspected and design specifications were reviewed. A summary of the tests on the 1.5 KW unit is included. A number of design modifications were made to permit an increase in the rating of the design to 28 volts at 1800 watts. Refurbishing of the breadboard system was completed.

Fabrication of the fuel cell breadboard system for shipment to MSC is progressing as planned and the contractual delivery date of November 5, 1964 appears valid. This unit, rated at 1.8 KW at 29 $\pm$ 2 volts, will be tested by NASA.

During the reporting period, Modification Number 6 to Contract NAS 8-2696 was executed. The modification covered expanded and extended research and development on fuel cell systems. Significant effort was applied to the preparation of the technical plan and quality assurance plan. The overall Program Plan was submitted to NASA in the form of an Operating Manual for the project. Included in the manual were the coordinated plans for the three task parts, PERT schedules, organization diagrams, definitions of responsibilities, laboratory procedures, and documentation requirements.

A series of two-cell tests were run to evaluate various cell constructions. An evaluation summary of these tests is included under Part I Tasks.

Results of preliminary testing of a breadboard model of an electronic controller for a vapor pressure regulator are also reported on.

author

# INTRODUCTION

## SCOPE OF WORK REPORTED

Modification Number 6 to Contract NAS 8-2696 was executed during this reporting period and has an effective date of August 14, 1964. Prior to this effective date work was done under Modification Number 3 to Contract NAS 8-2696.

This report, therefore, covers the conclusion of the work under Modification 3 and the start of the work under Modification 6.

## OBJECTIVE OF MODIFICATION 3 TO NAS 8-2696

Modification 3 to Contract NAS 8-2696 covered research and development work on the evaluation and design of a hydrogen-oxygen capillary-type fuel cell system and the fabrication of a 28 volt, 1.5 KW fuel cell assembly for verification of the evaluation and design.

## OBJECTIVE OF MODIFICATION 6 to NAS 8-2696

Modification 6 to Contract NAS 8-2696 further amplifies the work under this contract "to accomplish adequate research and development of materials and process and to establish engineering criteria that will assure an operational (fuel cell) system for space vehicle applications".

To accomplish these contract objectives the work is divided into the following three major task groups.

| | | |
|---|---|---|
| Part I Tasks | - | Research and Technology |
| Part II Tasks | - | Breadboard and Experimental Items |
| Part III Tasks | - | System Test Models |

Part I Tasks - Tasks include research studies, analyses, and tests to produce an advance in technology for improving the space electrical power systems which are being developed. The following areas of fuel cell technology are to be investigated:

(a) Water Transport Studies
(b) Cell Performance Characteristics
(c) New Plate Designs; Seal and Gasket Material Evaluation
(d) Cell Configuration Studies
(e) Thermal Analysis Program
(f) Coolant Gas Safety Studies
(g) Water Recovery Methods
(h) Overload Capabilities Analysis
(i) Advanced Control Methods
(j) Reactant Impurity Studies
(k) Shelf Life Determination

Work on Part I Tasks will continue throughout the life of the contract.

Part II Tasks - Tasks include the early building of an experimental fuel cell system using August 1964 technology. This unit will be delivered to NASA, MSC, Houston, Texas, for their testing and evaluation to establish mid 1964 technology and to assess early in the contract the problem areas that may exist which would require particular attention in the development program. Two additional breadboard type fuel cell systems will be built and used by Allis-Chalmers for in-house development testing.

Part III Tasks - Tasks include the development and building of eight 29 volt, 2000 watt power systems for testing and evaluation purposes. These advanced systems will include all necessary controls and subsystems for self-sustained operation. Two types of power systems will be delivered. The open loop type, will be designed to vent the by-products of the fuel cell reaction (heat and water vapor) directly to space. The closed loop type will be designed to recover the by-product water to provide a source of potable water. Tests and evaluations will be performed by both NASA and Allis-Chalmers. The following Fuel Cell Systems and Components will be built:

| System Number | TESTING PROGRAM | | |
|---|---|---|---|
| | Allis-Chalmers | MSFC | MSC |
| 1 * | In-house | ----- | ---- |
| 2 ** | In-house | ----- | ---- |
| 3 * | Acceptance | Environmental | ---- |
| 4 ** | Acceptance | ----- | System |
| 5 * | Systems and Subsystems | Engineering (Refurbished) | ---- |
| 6 *** | Components and Subsystems | ----- | ---- |
| 7 *** | Components and Subsystems | ----- | ---- |
| 8 * | Acceptance | Environmental and Design | ---- |

* Open Loop

** Closed Loop

*** Equivalent Modules and Components

## RESULTS OF TESTING OF 1.5 KW EXPERIMENTAL FUEL CELL SYSTEM

Testing and analysis of the 1.5 KW experimental breadboard was completed during this report period. The following is a description of the testing accomplished and an analysis of the test data obtained.

### Instrumentation

(a) Thermal

Seventy-two thermocouples, in conjunction with a three-position switch and twenty-four point temperature recorder, were utilized to monitor the system's thermal characteristics.

Fifty-two of the thermocouples were positioned in the oxygen plates of the module stack. There were thirty-five common oxygen plates corresponding to the thirty-five sections of the module; each plate serving two cells. The remaining twenty thermocouples were used to sense end plate, canister wall, and primary and secondary coolant temperatures. Figure 1 shows the location of the secondary coolant sensor instrumentation.

Number 30 gauge iron-constantan thermocouple wire was used from the installation to the copper junction block of the three-position switch. Number 20 gauge Teflon-coated copper wire was used from the switch to the 24-point recorder. Thermocouple junctions were coated with an insulating lacquer and then covered with Teflon tape before insertion into connector pins.

(b) Pressure

The pressure within the canister surrounding the module was measured with a static pressure connection located at the top of the dome. This sensed the pressure at the discharge of the heat exchanger and the suction side of the circulating fans. As this was the lowest pressure point in the system, it was used as the reference pressure for all other pressure readings.

The discharge pressure of the circulating fans was measured with a total pressure tube located within the supply duct 10 inches from the fan. This reading was the $\Delta P$ rise through the fan since the reference pressure was at the fan suction.

The inlet pressure to the heat exchanger was measured with a pressure tube pointed toward the end plate about one inch from the face of the cooler. See Figure 2 for the exact location fo this pressure probe.

The static pressure connection located at the end of the supply duct on the A-C side gave the pressure drop in the return passage and through the heat exchanger.

The pressure of the reactant gas and water removal cavity was measured with 0 - 50 psia pressure transducers. The flow of reactants and coolant was measured with calibrated flowmeters.

<u>Summary of Pressure Measurements</u>

1. Reference Pressure

   Fan Suction - Top of canister. Also used as total canister pressure.

2. $\Delta P$ - Circulating Gas Fan

   Discharge pressure measured in cooling duct $8\frac{1}{2}$" from top plate. Total Pressure. One for each fan.

3. $\Delta P$ - Across Heat Exchanger

Inlet measured at point one inch from cooler to top plate; 3-3/4" from common centerline of fans and 3/4" from other centerline.

4. $\Delta P$ - Across Heat Exchanger and Return Passage

Static pressure was measured at the bottom of cooling duct on side A-C.

(c) Electrical

The output of the module was measured with a dc voltmeter and a dc ammeter. The power input to each of the circulating fans was monitored with a voltmeter, ammeter, and wattmeter.

Individual section voltages were monitored by means of leads passing through specially constructed potting fixtures positioned in the bottom end plate.

## Test Description

The initial series of tests on the experimental breadboard had three main objectives. A definition of series-parallel 28 volt nominal fuel cell reactor performance was to be obtained concurrently with characteristics of a secondary gas coolant heat removal system. The third objective was to define the proper cavity pressure setting to effect static moisture removal over the design electrical load range. During the system's definition no attempt was made to optimize purge requirements. Thermal characteristics of the breadboard system along with proper cavity settings were defined at 1/3, 2/3, and full load, and at 33% overload. Voltage-current density performance was monitored at discreet intervals, and values were defined at 1/6 full load increments from no-load to 66% overload.

## Test Sequence

The first test was performed utilizing gaseous helium as the secondary coolant supply and water as the primary coolant supply. Reactor load level was approximately 20 amperes (50 ASF) with canister and reactor pressure held at 35 psia and inlet fin passage temperature held at 190° F. Cavity pressure was initially set at 213 mm Hg (40% KOH and 195° F) and subsequently adjusted for best performance. A 15 second reactant purge was set to occur at intervals of 15 minutes. The excess flow corresponded to approximately 3% of stoichiometric reactant consumption.

After a cursory analysis of the data obtained from the helium test, the remaining tests in the definition series were run utilizing hydrogen as the secondary coolant and water-glycol (60% by weight) as the primary coolant. With the reactor at atmospheric pressure, the canister was evacuated and purged with hydrogen to flush out as much of the inerts as possible. Reactor pressure was returned to 35 psia and individual open-circuit voltages were noted. The reactor was then heated to a 190° F inlet fin passage temperature with proper cavity pressure defined from the previous test. Runs of 24 hours at approximately 20, 40, 60, and 80 amperes were conducted to define or confirm proper cavity pressure at each level. Thermal data was collected.

Utilizing the cavity pressure and purge magnitude defined at the 60 ampere load, tests at 40 and 20 ampere loads were performed, each of twelve-hour duration. Differences from previous tests at the respective loads were noted and voltage-current density data was recorded at arbitrary intervals.

## Results of Test

The nominal 28 volt, 1.5 KW experimental unit successfully operated for 162 hours under load. Only normal fuel cell degradation, associated with nickel electrode construction, was noted during this period. The average section dropoff was 0.20 millivolts per hour at 100 ASF and 0.40 millivolts per hour at 200 ASF.

This contrasted to single cell dropoffs of 0.10 millivolts per hour and 0.15 millivolts per hour, respectively, recorded in previous tests. The secondary heat removal blowers, although inadequate in capacity, provided tolerable thermal control. The vacuum cavity controller, although requiring considerable manual manipulation for thermal compensation, did provide the desired cavity settings.

At the outset of the test, meaningful thermal data could not be obtained on the system at the 20 ampere load, because the heat rejected at this load level was not sufficient to maintain the desired reactor temperature. Heat injected via the secondary coolant loop was required to maintain the specified test thermal conditions. This condition caused a slight modification in the test plan. Added thermal insulation would have decreased the amount of this heat loss.

Helium was used as the secondary coolant during the initial 25 hours of operation. Hydrogen was substituted for the remaining tests. Water was utilized as the primary coolant during the entire operational period. The primary coolant flow was automatically controlled (full on or off) during those periods of time when cavity pressure settings, volt-ampere characteristics, or purge requirements were being defined. It was manually controlled to provide system thermal balance at the test load levels. The primary coolant inlet temperature was varied from 75° F to 135° F and the flow rate was varied as required.

Warmup of the system from room temperature to normal operating temperature required $1\frac{1}{4}$ hours. The warmup was achieved by heating the primary coolant and circulating it through the heat exchanger to heat the secondary gas coolant. The secondary coolant was then circulated in the normal manner, transferring the heat energy to the fuel cell module.

The purge rate, interval, and duration were held constant for the first 100 hours of operation. The purge was set at approximately 3% of reactant demand at full load. During the last 60 hours of operation, the purge rate was varied. The purge duration was reduced to a point where the total voltage began to decay. From this point the purge duration was increased while the purge interval was shortened.

A complete set of instrumentation readings was recorded at one-half hour intervals during the entire operating period. Each set of data was assigned a sequential run number.

## Load Profile

The reactor operated on a step load profile as shown in Figure 3.

Some apparent discrepancies between reactor voltage and power output can be noted in the profile, i.e., increasing voltage with increasing load or vice versa. The following is an explanation of these discrepancies related to time in the load profile.

| Elapsed Period | Explanation |
|---|---|
| 12.2 - 19.1 hours | Cavity setting decreased to 36% KOH from 37% |
| 19.1 - 25 | Cavity setting 37% and increased purge cycle |
| 25 - 43 | Operation after weekend shutdown |
| 68.5 - 71 | Slight degradation in performance noted |
| 119.5 - 131.3 | Purge duration 6 seconds |
| 131.3 - 139.3 | Purge duration 9.5 seconds |
| 139.3 - 146.6 | Purge duration 10 seconds, volt-ampere curve taken, and slight alterations in water cavity setting |
| 153.4 - 162.3 | Cavity leak and purge cycle manipulations |

The average reading of the four thermocouples imbedded in the oxygen plates was used to define an operating temperature. With this temperature and a pre-determined KOH concentration the corresponding cavity controller pressure setting was defined from Figure 4. The optimum cavity setting for operation at all load levels was found to correspond to a 37% KOH concentration. The pH readings taken from water samples varied between 6.9 and 9.8 with the majority falling in the 7.0 to 8.0 range.

## Electrical Performance

Voltage-current density characteristics were recorded at 5, 65, 101, and 140 hours of elapsed operating time. Observations were not taken at or around the 160 hour period due to the unanticipated events which terminated the test. Both total and individual section voltage values were recorded.

Figures 5 and 6 summarize data obtained. Total or average section voltage is based on the measurements taken from all 35 sections.

## System Pressure and Thermal Characteristics

During the 162 hours of operation various levels of steady state electrical load were achieved and maintained for sufficient duration to obtain an indication of secondary gas coolant subsystem performance as well as fuel cell thermal characteristics. The system was placed in thermal equilibrium by maintaining a fixed primary coolant inlet temperature and varying the primary coolant flow rate until the reactor internal temperatures (average sections 16 and 21) were stabilized. This set condition was then maintained for approximately $1\frac{1}{2}$ to 2 hours during which time the steady state thermal and pressure characteristics were recorded.

Of the many sets of data taken under these conditions, a selected but representative number of test runs typical of 40, 50, 60, and 80 ampere loads are summarized in Table I. A definition of the terms used in the table is included with the table.

The first set of data (column C) was obtained with a 39.5 ampere load ($\sim$ 2/3 full load), helium as the secondary coolant, and a primary coolant (distilled water) inlet temperature of 133°F. The next seven columns of data (D through H), with loads as noted, utilized hydrogen as the secondary medium, various fixed primary coolant inlet temperatures, and the first of two sets of hydrogen blowers used in the testing period.

The bearing failure of one blower of the initial set at 101 elapsed hours resulted in replacement of both blowers, per the vendor's recommendation, with single phase units. It was the manufacturer's belief that the new units would give essentially the same performance but much longer life. The last two sets of data (O and P) are again with the hydrogen secondary coolant at the conditions noted, but reflect the performance of the second set of circulating blowers. A significant decrease in blower characteristics is noted in comparison to the initial set.

A thorough review of the temperature data recorded during the breadboard operation indicated, with a few exceptions, that the prescribed thermal characteristic was obtained and the results were valid. Exceptionally good data was obtained from the sensors imbedded in the oxygen plates of reactor sections 16 and 21.

There were three general areas in which the temperatures recorded were not indicative and could not be correlated.

(a) The cell plate fin measurements taken at the secondary coolant fin passage entrance (along the inlet duct) all appeared to be biased to some extent. The magnitude of the observed temperature, near to the inlet duct, increased from the top end plate (blower exit) along the reactor length to the bottom end plate. In contrast, the plate fin measurements taken at the fin passage exit increased along the length of the reactor to the center section and then began to decrease toward the bottom end plate. The latter trend was more reasonable as one would expect a relatively symmetric thermal gradient to exist about the middle of the stack length. The sheath in which the thermocouple was placed was sufficiently cooled by the secondary coolant in the inlet duct by means of conduction, to bias the true plate fin reading.

(b) The primary coolant thermocouples placed in the aluminum fitting just forward and aft of the heat exchanger gave some very erratic readings and could not be correlated to the data recorded from the primary coolant measurements taken in the lines external to the canister. The erroneous information obtained was believed to have resulted from a second thermoelectric junction formed in the return passage. This conclusion was based on the fact that a number of the readings were at or near the secondary coolant temperatures recorded in the return passage. Since the thermocouple lead was not continuous from the installation through the potting fixture but was spliced inside of the canister, a secondary junction was formed. A check on the installation prior to startup, at the 101 hour elapsed shutdown, and during post checkout, did give a true temperature readout.

(c) A third area of primary concern was the secondary coolant thermal data obtained from just aft of the heat exchanger and from forward of the blower inlet. The temperature recorded by the thermocouple located just aft of the heat exchanger on side B-D was consistently 8 degrees lower than the temperature recorded at the blower exit on that side. In contrast, the temperature recorded on side A-C was consistently 2 to 3 degrees higher than that recorded at the blower exit on that side. Data recorded forward of the heat exchanger at two locations and aft of each blower exit plane was consistent within instrumentation errors. There presently is no conclusion that can be drawn for this anomaly unless that it is a function of the secondary coolant flow field.

The average of these two temperatures, in conjunction with the temperature recorded forward of the heat exchanger, was utilized to define the weight flow rate, or, with the calculated density, to define the volume flow rate for the secondary coolant. The blower performance noted in the summary table was computed on this basis.

From measured data and pressure values, an envelope of the estimated system $\Delta P$ was drawn up. To minimize the cell gradient to approximately 7° F a previous calculation imposed a required hydrogen flow rate of 75 cfm per fan, corresponding to approximately 0.96 inches of $H_2O$ pressure drop.

## Conclusions and Recommendations

The following comments were made after analysis of the tests which were run on the 1.5 KW module.

### Temperature Measurements

The installation utilized for measuring fin plate temperature was a thermocouple imbedded in a sheath which was inserted in a tapered hole in the cell plate fin. Due to its construction, the sheath lost some heat energy to the surrounding gas and gained some heat energy from the fin of the cell plate. Therefore, the temperature of the thermocouple was at some point between the fin temperature and surrounding gas temperature. A modification of the thermocouple design for the cell plate fin will be made during refurbishment of the unit.

The thermocouples installed in aluminum fittings of the coolant lines near the heat exchanger within the canister did not appear to be reading the true coolant temperature. The thermocouples installed in the coolant lines external to the canister appeared to be reading the true temperature. These latter temperatures were used for the heat balancing calculations.

### Radiation Losses

There was a considerable variation in the amount of radiation losses calculated at the higher loads. This variation could be due to the inaccuracy of test data obtained. The radiation loss is based on the thermal heat balance of the unit. It is the difference between the theoretical heat generated within the unit plus the power input to the secondary coolant circulating fans, and the heat removed by the heat exchanger (based on data).

## Fan Performance

At the end of the first 100 hours of operation, a failure occurred in one of the off-the-shelf secondary coolant circulating fans. Visual inspection indicated that the failure was due to a malfunction of one of the bearings. This failure was discussed with the vendor who indicated that it must have been the result of operating the unit in a low density atmosphere. The vendor recommended that a varying flow density, high-altitude, motor-driven fan be used. Such fans were installed in the unit and were operated approximately 60 hours with no apparent mechanical difficulties. A verification test was run on one of these fans. This test as well as the results of the 1.5 KW module performance test revealed that these fans did not develop as much head as the first units. A concentrated effort should be expended to obtain the circulating fan performance necessary to minimize the active area thermal gradient.

## Water Removal Cavity Control

To eliminate manual adjustment a more sophisticated control should be developed to automatically adjust the pressure of the water removal cavity to compensate for cell temperature variations. Both a mechanical and an electronic temperature compensated vacuum control is being developed.

## Circulating Coolant Control

The present control functioned very well at steady load conditions. However, each time the load was changed, the control had to be reset to maintain a constant cell temperature. A more constant internal cell temperature may have been more fully realized if the sensing thermocouple had been within the cell instead of the cell plate fin.

## Power Circuit Control

No trouble was encountered with the present power circuit control.

## Purge System

The purge system functioned as programmed.

## Reactant Supply Subsystem

There were no indications of any malfunctions of this system.

## Primary Coolant Inlet Temperature

The desired or limiting coolant inlet temperature was maintained by regulating the flow of cooling water to the external cooler. At times it was advantageous to use a mixture of cold water and steam to obtain a high inlet temperature of the coolant (above 100° F). With the maximum flow of cold water to the external cooler the coolant inlet temperature was 80° to 90° F. These tests were run with distilled water. In the near future the module should be run with the primary coolant a mixture of 60% methanol and 40% water, by weight, since the primary to secondary coolant heat exchanger was designed to these requirements and may not operate as effectively with distilled water.

## Static Moisture Removal Subsystem General Conclusions

A 28 volt 1500 watt breadboard fuel cell system utilizing the Static Moisture Removal System has been constructed and successfully operated for 162 hours under load. Several periods of operation were demonstrated at 2000 watts and at a brief overload of 2580 watts, which is equivalent to 172% of rated load.

The Static Moisture Removal System has been proven by feasibility and breadboard tests to be continuously operable over a range of cell loads up to 214 $ma/cm^2$. Tests on the 28 volt breadboard system have further simplified the system by verifying water removal from only one side of the cell.

Tests conducted on single fuel cell units employing the Static Moisture Removal method have demonstrated extended operation at current densities of 300 $ma/cm^2$ and above.

The Static System is well suited for operation in a space environment since water transport occurs in the vapor state and all liquids in the system are contained in capillary pores. Where recovery of product water is not desired, a significant thermal advantage is realized with this system. About 35 percent of the waste heat burden produced in the cell may be ejected directly to space vacuum as latent heat of vaporization of the product water, thus reducing the heat burden imposed upon the space vehicle rejection system.

The Static Moisture Removal Method in a non-condensing system eliminates the requirements of recirculating reactant pumps, condensers and gas-water separators. The absence of these components and their associated parasitic power requirements, valves, piping and connections makes static moisture removal an inherently more efficient and reliable system.

## PART I TASKS - RESEARCH AND TECHNOLOGY

Part I Tasks include research studies, analyses and tests to be conducted to produce an advance in technology for improving the space electrical power systems to be developed. The areas of particular interest are:

(1) Methods of water recovery and storage of water in a zero gravity environment.

(2) Improved and simplified thermal controls.

(3) Development of mathematical models of fuel cell systems from which system performance can be predicted and optimized.

(4) Continued parametric studies of capillary type fuel cells.

### Technical Plan

During the reporting period the technical plan for the Part I Tasks was developed. Each item under the work scope was broken down in sufficient detail to permit construction of a PERT chart and a list of activity descriptions.

### Technical Progress

#### Evaluation Tests of Cell Centerline Specification

A series of tests were conducted using two-cell parallel arrangement test cells to evaluate the preliminary centerline specification. These test cell assemblies utilized Allis-Chalmers silver electrodes and various anode structures and were tested to observe the variations in performance between the several designs. Table II shows the construction details of these test cells.

**Test Conditions** - All tests were continued for a minimum period of 50 hours, or until failure, with the following load profile:

| Time | Total Current |
|---|---|
| 0 - 10 hours | 40 amperes |
| 10 - 40 hours | 64 amperes |
| 40 - 50 hours | 80 amperes |

The tests were conducted with a cell temperature of 190° F and a reactant pressure of 22.0 psig.

**Discussion of Experimental Results** - Table III summarizes the pertinent cell parameters observed during the tests. Reference to Table II will reveal the comparisons which should be made.

To gain a feeling for the magnitude of the performance variation between similar cells the groups 31 and 32, 34 and 36, 35 and 37 can be compared. The only difference within a group was the number of support plaques. This parameter would not be expected to affect cell performance. The voltages at 200 ASF:

Voltage at 200 ASF

| Number of Support Plaques | 1 | 2 | $\Delta V_2 - 1$ |
|---|---|---|---|
| | .77 | .81 | .04 |
| | .797 | .806 | .009 |
| | .81 | .78 | -.03 |
| Average | .7923 | .7986 | |

If it assumed that the six voltage measurements listed above are drawn from a normally distributed population of cell voltages, the properties of the population from which the sample was drawn can be inferred. That is, the mean voltage and standard deviation of an infinitely large set of cell voltage tests can be estimated. The confidence limits of the estimates depend on the size of the sample taken, which in this case is six. The estimate of the mean value is merely the average of the test values,

$$M = \frac{1}{N} \sum V_i \qquad = \qquad .796 \text{ volts}$$

where:

M is the mean value

N is the number of tests

$V_i$ is the voltage of the $c^{th}$ test

The standard deviation estimate of the voltages around the mean is given by

$$\sigma = 0.017 \text{ volts}$$

For a sufficiently large number of tests, 68% of the test values will lie in the range of $0.796 \pm 0.017$ volts, 95% will lie in the range of $0.796 \pm 0.034$ volts. This assumed that M and $\sigma$ were correctly estimated. Since only six measurements were taken it cannot be said with certainty that the mean is 0.796 or the standard deviation is 0.017. It can only be said that there is a certain probability that these two values lie within a certain band. It can be shown by R. A. Fisher's T distribution that for the case at hand:

| Probability of True Mean Lying Within Confidence limits | Confidence Limits |
|---|---|
| 99.9% | 0.748 - 0.844 |
| 99 % | 0.768 - 0.824 |
| 95 % | 0.778 - 0.814 |

The estimate of the standard deviation for the fuel cell voltage is also not a true value, but here again only the midpoint of a band which has a particular probability of including the true but unknown value of $\sigma$ . The wider this band is chosen, the more probable it includes the true value of $\sigma$ .

The mean value of cell voltage for one support plaque fuel cells is extremely close to mean value for the two plaque cells, i.e., within 0.0063 volts. Since this difference is very much smaller than the uncertainty attached to each of the mean values, it is of no statistical significance. This would indicate that there is no variation of cell voltage with the number of support plaques used.

The four types of anode material which were tested were designated:

(1) Clevite No. 1
(2) Clevite No. 2
(3) A-C 464
(4) A-C 564

Comparison of the effect of anode material on performance was made by studying the column variation of the following groupings.

| | Voltage at 200 ASF | | $\Delta V$ = V average - V | |
|---|---|---|---|---|
| Number of Support plaques | 1 | 2 | 1 | 2 |
| Type of Material | | | | |
| Clevite No. 1 | .77 | .81 | .022 | -.018 |
| Clevite No. 2 | .797 | .801 | -.005 | -.014 |
| A-C 464 | .81 | .78 | -.018 | .012 |
| A-C 564 | --- | .771 | --- | .021 |
| Average | .792 | .792 | -.0003 | .0003 |

The trend in the column for one support plaque is not the same as the trend in the column for two support plaques. Thus, it must be concluded, that within normal current density ranges, the variations of anode base material which were tried had no significant effect upon cell performance.

The trend in performance due to a change in the plating density of catalyst on the anode was obtained by comparing cells 34 (30-30) and 39 (20-20).

| Catalyst Density | Voltage at 200 ASF |
|---|---|
| 30-30 (30 mg/in$^2$ Platinum - 30 mg/in$^2$ Palladium | 0.797 |
| 20-20 (20 mg/in$^2$ Platinum - 20 mg/in$^2$ Palladium | 0.796 |

Thus, within the range of catalyst plating density tested, no variation in cell performance was evident.

Variation of cell voltage at constant current density as a function of membrane thickness should be due to the change in voltage drop across the electrolyte. This is expressed by the equation

$$\Delta V = \frac{\tau}{P} \frac{J}{\sigma} \Delta \ell'$$

When $\tau$ is the tortuosity $\approx$ 3, and is defined by: equivalent distance traveled by an ion = $\tau$ x straight line distance. P is the porosity of the asbestos and is used here in the expression A - PA' where A is the actual area through which an ion can move, and A' is the normal cell surface area. J is the current density, and $\sigma$ is the electrolyte conductance which has been experimentally determined for KOH - $H_2O$ solutions. For 200 ASF, normal operating temperatures and concentration, and a change of length of 0.01 inches, the expected change in voltage would be:

$$\Delta V = \frac{3}{.7} \times \frac{200}{1.6} \times 0.01 \left(\frac{1}{2.54 \times 144}\right) \text{ volts}$$

$$= 0.0146 \text{ volts}$$

This should compare with the voltage difference at 200 ASF, of the group 39, 40. The observed cell voltages at 200 ASF were:

| Cell Number | Spacing | Voltage at 200 ASF |
|---|---|---|
| 39 | 0.03 | 0.794 |
| 40 | 0.02 | 0.840 |
| | = | 0.044 |

The fact that the measured value was 30 millivolts high could be attributed to random cell-to-cell variation or an erroneous estimate of $\mathcal{T}$ , the tortuosity factor. Further testing of the statistically significant groups must be performed to establish the cause of the discrepancy.

Cells 42, 44, and 45 experienced difficulty and had to be shut down prior to completion of the original test programs. These cells contained anodes which had been replated with catalyst from densities of 20 mg/in$^2$ Platinum - 20 mg/in$^2$ Palladium to 30 mg/in$^2$ Platinum - 30 mg/in$^2$ Palladium. Tests were run on the anode of cell 42 to determine its plating density, surface area, and porosity. The results were:

| | Original (30-30) | Replated (20-20 to 30-30) |
|---|---|---|
| Measured Density | (27.9-29.6) mg/in$^2$ Pt | (27-29.7) mg/in$^2$ Pt |
| | (28.1-29.4) mg/in$^2$ Pd | (25.5-29.9) mg/in$^2$ Pd |
| Measured Surface Area | (1.22 - 1.32) m$^2$/gm | (1.25 - 1.64) m$^2$/gm |
| Measured Porosity | (72.3 - 73.1) % | (73.5 - 72.5) % |

The above physical parameters show no obvious difference between the two types of anodes. It is possible that other measurements may show some differences.

It is also possible that the short cell life is in no way connected with the type of anode used.

Teardown reports on most of the cells noted that there was a white deposit on the hydrogen electrode, usually near the gas inlet. A sample of this material was obtained from cell 38 and chemically analyzed. The results were:

$$CO_2 \text{ - } 24\% \qquad\qquad K \text{ - } 28\%$$

These are roughly the percentages which would be expected if the material were $K_2CO_3$ (32% and 28%). In cell number 38 only one of the hydrogen electrodes had any observable white deposit, the other electrode appeared to be clean. Analysis of the KOH in the asbestos may have revealed the presence of $CO_2$. This was not done. This could also explain the reason why white deposits were not noted in most previous cells. It is also possible that a less pure gas was used, or that connections between the tank and the cell are not being made as well as previously.

Figure 7 shows the observed average performance of cells 31 - 40. The apparent degradation of performance with time may be due to a bias such as inert buildup or cell terminal corrosion. The observed decay was 0.3 millivolts per hour at 200 ASF. Cell number 38 shows only about 0.1 millivolt per hour at 200 ASF.

Conclusions and Recommendations

(1) No observable effect on cell performance due to the use of one or two support plaques.

(2) No observable effect on cell performance with catalyst loading in the range of 20-20 - 30-30.

(3) No difference in lot numbers of Clevite electrodes.

(4) No difference in A-C 464 or Clevite anode.

(5) Statistical scatter of cell performance within a group of cells is expected to be large. Many of the parameters which we wish to measure are small. Thus, in future tests, statistically significant samples should be used.

EXAMPLE

The standard deviation of the group of six cells assumed to belong to the same family was estimated to be $\sigma = 0.017$. By using properties of the normal distribution it is possible to specify the number of separate tests N which must be considered in order to be able to say that the true mean lies within a certain band $\delta$ V with a probability P.

| P | $\delta$ V | N |
|---|---|---|
| 90 % | 0.008 | 12 |
| | 0.016 | 3 |
| 95 % | 0.008 | 17 |
| | 0.016 | 4 |
| 99 % | 0.008 | 30 |
| | 0.016 | 8 |
| 99.9 % | 0.008 | 49 |
| | 0.016 | 12 |

## PART II TASKS - BREADBOARD AND EXPERIMENTAL ITEMS

Part II Tasks include the building of an experimental fuel cell system using current technology (August 1964) and the refurbishing and modification of an existing 1500 watt system. The refurbished and modified system (A-C BB No. 1) is rated at 1800 watts at 29 volts, and will be subjected to verification testing at Allis-Chalmers. The other rated at 1800 watts at 29 volts, will be acceptance tested and delivered for further testing by NASA, MSC Houston, Texas. Another 28 volt, 2 KW breadboard system (A-C BB No. 2) will be built and used for continued development testing at Allis-Chalmers in support of Part III Tasks. These systems will differ from the later advanced systems to be developed in that the electrical and fluid control hardware will be panel mounted on test boards.

### Technical Plan

Prior to the initiation of work on the Part II Tasks, a review of the work scope was made and a detailed schedule and technical plan was formulated. The technical plan and PERT schedule were included as part of the Operating Manual submitted to NASA.

### Technical Progress

The 1500 watt fuel cell system described in the first part of this report was dismantled and inspected. A Support Plate Log was initiated, at this time, to provide an active history of all cell plates.

A design review of the 1.5 KW experimental unit reactor assembly, controls, and instrumentation was made in preparation for modification and rebuilding of the system.. The disassembled condition of the reactor, performance data obtained during the 162 operating hours previously logged, and general operating techniques required during the test were used as a criteria for the review.

## Fuel Cell System Modifications

A number of design modifications were executed to enhance the system performance of the Part II breadboards. The nominal ratings of the Part II breadboards have been increased to 1.8 KW for the MSC breadboard and A-C BB No. 1, and increased to 2.0 KW for the Allis-Chalmers breadboard No. 2, as shown on the abbreviated performance specification included with this section. The modifications incorporated into the redesign of A-C BB No. 1 and the MSC breadboard are summarized as follows:

(1) Cathode material changed from nickel to silver

(2) Support plaques used on both side of water removal membrane instead of only on the vacuum side

(3) Increased clearance for cell gaskets

(4) Increased secondary coolant passageways between hydrogen and water removal plates

(5) Improved temperature instrumentation installation techniques.

### Instrumentation

A review of temperature measurements taken during initial operation of the 1.5 KW unit indicated that some of the data was biased. The specific areas of concern were oxygen plate temperatures recorded in the inlet duct region and redundant measurements taken internal to the canister just before and aft of the heat exchanger. In both cases, temperatures were apparently influenced by secondary coolant conditions in their respective areas. A new thermocouple installation has been tested which should eliminate this problem.

# ABBREVIATED PERFORMANCE SPECIFICATION

# FOR A-C AND MSC BREADBOARD UNITS

| | |
|---|---|
| Fuel Cell Module Design: | 35 series connected sections, each composed of two parallel connected cells with each cell having 0.2 $ft^2$ active area. |
| Rated Power: | 1800 watts nominal - MSC and A-C BB No. 1<br>2000 watts nominal - A-C BB No. 2 |
| Voltage Regulation: | MSC Unit - 29 $\pm$2 volts, d.c. from 800 to 1800 watts gross<br>A-C BB No. 2 - 28 $\pm$ 2 volts, d.c. for normal load variations |
| Module Operating Temperature and Pressure: | 195 $\pm$ 5 °F and 37 psia |
| Performance Requirements: MSC Unit | 500 to 1400 watts for 200 hours, continuous<br>1800 for six hours duration |
| A-C BB No. 2 | 800 to 2000 watts for 720 hours |

## Thermal Control System

| | |
|---|---|
| Primary Coolant: | Water glycol or distilled water at inlet temperature of 70 $\pm$10° F |
| Secondary Coolant: | Helium or hydrogen at 175 $\pm$ 10° F |
| Canister Pressure: | Charged and maintained at 40 psia and maintained within $\pm$ 1 psi. |

## Controls

The design of the electronic fuel cell water vapor cavity controller has been reviewed. From operating experience gained during breadboard unit operation, and from an analysis of the basic circuit, the controller was modified to provide the following features:

(1) Percent KOH selector control

(2) Provision for a range of pressure transducer characteristic slopes

(3) Temperature compensation within a range of 100 to 225° F

(4) Elimination of overshoot through a proportionate error correction, variable duty cycle, trigger circuit for the vacuum solenoid valve.

A breadboard of this temperature compensated controller has been built for verification testing. Initial testing has been successful. In addition to the electronic vacuum control development, an effort is underway to design a mechanical temperature compensated vacuum regulator.

## A-C Breadboard No. 1 Refurbishment

The Allis-Chalmers 1.5 KW breadboard system was refurbished. The assembly and preliminary system checkout were completed September 21, 1964. Configuration logs and check sheets were implemented for record purposes.

Components for A-C fuel cell assemblies and canisters were received, inspected and identified according to planned quality control procedures. Vital materials such as asbestos, electrodes, plaques, support plates, catalyst materials, etc., were brought under lot control procedures.

The system testing was initiated and is still in progress. The initial performance characteristics of the unit are shown in Figure 8.

## MSC Breadboard Unit

All major components for the fabrication of the MSC 1.8 KW breadboard were under construction by the end of August. The required cell plates, which are a long lead item in the fabrication, were completed on August 21, 1964. An inventory of raw materials, and of finished components was initiated early in the reporting period.

All components for the fuel cell assemblies and canisters were received, inspected and identified in accordance with planned quality control procedures.

Fabrication of the MSC 1.8 KW breadboard has progressed on schedule. Some subassemblies have been completed and the stacking of the MSC fuel cell module was completed.

The configuration and requirements of the MSC interface board which will be delivered with the fuel cell assembly, were received and the interface board was designed.

Fabrication of the checkout board and the interface board for the MSC 1.8 KW unit have been completed and the assembly of the boards has started.

## PART III TASKS - SYSTEM TEST MODELS

Part III Tasks include the development and building of eight advanced 29 volt, 2000 watt power systems for testing and evaluation purposes. These advanced systems will include all necessary controls and subsystems for self-sustained operation. Two types of power systems will be delivered. The open loop type, will be designed to vent the byproducts of the fuel cell reactions, heat and water vapor, directly into space. The closed loop type will be designed to provide a source of potable water. Tests and evaluations will be performed by both NASA and Allis-Chalmers.

### Technical Plan

Tasks were reviewed in depth and a technical plan for the Part III Tasks and a quality assurance plan was prepared. A detailed PERT plan and a list of activity descriptions were prepared.

Preliminary plans have been written to formalize flow of paper work from inception of Purchase Requisition through to Receipt, Acceptance and Storage of material and parts for this project. The procedures will provide complete traceability of materials and parts into sub-assemblies and assemblies.

### Technical Progress

A design has been evolved for a temperature compensated vacuum regulator with the intention of building and testing a prototype model. A preliminary concept of a fuel cell primary coolant control was finished and the assembly of a breadboard model of it has begun. An investigation of methods of maintaining a constant fuel cell load current was initiated. This constant current load device will be useful in laboratory testing. Verification tests on an electronic controller for a vapor pressure regulator were completed.

Procurement specifications for improved system control components such as reactant regulators, solenoid valves, etc., specifically designed and sized for their intended application are being reviewed and revised as required. Test specifications for these components are also being written.

## Electronic Controller for a Vapor Pressure Regulator

The KOH electrolyte concentration in an operating fuel cell is dependent upon the operating temperature and the vapor pressure in the water removal cavity as shown in Figure 4. A temperature compensated, electronic controller circuit for regulating this cavity vapor pressure has been developed. The developed circuit design permits the direct application of commercially available microminiature construction.

Basically the vapor pressure regulator will sense the cell temperature and adjust the water removal cavity pressure to maintain a preset electrolyte concentration.

Calibration tests of a breadboard model of this controller were run using a mock fuel cell, and finally the controller was tested on an operating fuel cell system..

Typical test results are shown in Figure 9. These results show that the controller is capable of keeping the fuel cell at an optimum electrolyte concentration over a wide range of cell temperatures. The present compensation range is from 120 to 230° F.

## TEST DATA DEFINITIONS FOR TABLE I

The Table I, Test Summary, lists the measured and computed system characteristics for a number of load levels. The run depicted for each is typical of three to five runs taken during the test interval at the prescribed input conditions. Listed below are definitions of the terms used in the table.

| | | |
|---|---|---|
| Item 1 | Secondary Gas Coolant - medium which transport reactor thermal burden to primary coolant loop | |
| Item 2 | Sequential run number - Number identifying data taken at one-half hour intervals during the test and referenced to the start | |
| Item 3 | Elapsed Operating Time - the actual time that the unit had been operating when the data was taken | |
| Item 4 | Load Amperes - taken from log sheet | |
| Item 5 | Total Reactor Volts - taken from log sheet | |
| Item 6 | Gross Output Watts - product of volts and amperes | |
| Item 7 | Volts/cell - total volts divided by number of section | |
| Item 8 | Current density in amperes per square foot - load in amperes divided by the effective cell area in square feet. | |
| Item 9 | Theoretical heat rejected $= (150.5 - 3.41\,V)\,I_T =$ BTU/hour | |

$I_T$ = Total current - amperes

$V$ = Total volts

Test Data Definitions for Table I (continued)

| | |
|---|---|
| Item 10 | Primary coolant inlet temperature - distilled water temperature recorded (T/C 72) external to canister on inlet line to heat exchanger |
| Item 11 | $\Delta T$ Primary Coolant Heat Exchanger - distilled water temperature rise across heat exchanger measured external to canister |
| Item 12 | Primary Coolant Flow - distilled water flow rate measured with a calibrated flowmeter |
| Item 13 | Heat Removed in Heat Exchanger - product of primary coolant flow rate and temperature rise |
| Item 14 | Total Fan Input - power input to both circulating blowers measured with a wattmeter |
| Item 15 | Net Convective - Radiation Loss - Difference between theoretical heat generated within the unit plus the energy input to the circulating blowers and thermal burden removed by heat exchanger |
| Item 16 | $\Delta T$ Circulating Gas - secondary gas coolant temperature difference recorded across heat exchanger |
| Item 17 | Flow of circulating gas lbs/hour - heat exchanger thermal burden extracted divided by specific heat and temperature drop of gas across the heat exchanger |
| Item 18 | Canister Pressure - secondary coolant total pressure measured in the canister dome |

Test Data Definitions for Table I (continued)

| | |
|---|---|
| Item 19 | Flow of circulating gas - cfm/fan - flow in pounds per hour divided by density equals total volume rate in cfm. One-half of total volume rate will be capacity of one blower. |
| Item 20 | $\Delta P$ of circulating gas across fan in inches of water - taken from log sheet |
| Item 21 | $\Delta P$ across heat exchanger - inches of water taken from log sheet |
| Item 22 | $\Delta P$ across heat exchanger and return passage - taken from log sheet |
| Items 23 and 24 | Taken from temperature data sheets |
| Item 25 | Average $\Delta T$ Fin Temperature - difference between the average plate fin temperature at the fin passage exit plane and the plate fin temperature at the passage inlet |
| Item 26 | $\Delta T$ across active area - measured temperature difference across half width of cell active area taken at two sections |
| Item 27 | $\Delta T$ Plaque $C_L$ to fin exit - thermal gradient measured from center of cell active area to plate fin passage exit. |

TABLE I

| | TEST | C | D | G | K | H | I | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Secondary Gas Coolant | Helium | Hydrogen | Hydrogen | Hydrogen | Hydrogen | Hydrogen | Hydrogen | Hydrogen | Hydrogen | Hydrogen |
| 2. | Sequential Run Number | 62 | 78 | 93 | 181 | 116 | 132 | 207 | 215 | 264 | 323 |
| 3. | Elapsed Operating Time - Hours | 23 | 31 | 38 | 82 | 50 | 58 | 96 | 100 | 124 | 153 |
| 4. | Load - Amperes | 39.5 | 40 | 40 | 50 | 59.1 | 59.1 | 78.6 | 76.2 | 57.2 | 49.1 |
| 5. | Total Reactor Volts | 30.0 | 30.2 | 30.4 | 29.3 | 28.4 | 28.4 | 26.1 | 25.3 | 27.5 | 28.5 |
| 6. | Gross Output - Watts | 1186 | 1209 | 1214 | 1467 | 1679 | 1677 | 2052 | 1923 | 1572 | 1400 |
| 7. | Volts/Section or Cell | 0.867 | 0.863 | 0.867 | 0.838 | 0.812 | 0.811 | 0.746 | 0.721 | 0.787 | 0.815 |
| 8. | Current Density - ASF | 98.8 | 100 | 100 | 125 | 148 | 148 | 197 | 190 | 143 | 123 |
| 9. | Theoretical Heat Rejection - BTU/hour | 1900 | 1896 | 1880 | 2525 | 3166 | 3174 | 4834 | 4905 | 3240 | 2590 |
| 10. | Primary Coolant Inlet Temperature - ° F | 133 | 77 | 135 | 84 | 88.5 | 102 | 95.5 | 113.5 | 101 | 92 |
| 11. | $\Delta$ T Primary Coolant Heat Exchanger | 42 | 103.5 | 52 | 95.3 | 82.7 | 71.9 | 68.3 | 40.2 | 69.7 | 86.3 |
| 12. | Primary Coolant Flow - Pounds/hour | 41.2 | 16 | 31.5 | 23.5 | 38.5 | 38.5 | 63 | 107 | 42 | 24 |
| 13. | Heat Removed in Heat Exchanger - BTU/hour | 1730 | 1656 | 1638 | 2240 | 3184 | 2767 | 4302 | 4301 | 2910 | 2070 |
| 14. | Total Fan Input - Watts | 171.5 | 149.8 | 156.2 | 147.8 | 147 | 146.5 | 146 | 144 | 71.5 | 71.3 |
| 15. | Net Convection-Radiator Loss - BTU/hour | 753 | 746 | 771 | 789 | 584 | 918 | 1035 | 1099 | 579 | 782 |
| 16. | $\Delta$ T Circulating Gas - ° F | 11.5 | 7.4 | 7.5 | 11.0 | 10.8 | 13.0 | 18.5 | 20.2 | 15.0 | 11.7 |
| 17. | Flow Circulating Gas - Pounds/hour | 121 | 65.5 | 63.8 | 59.8 | 86.4 | 62.2 | 68 | 62.5 | 56.7 | 52.7 |
| 18. | Canister Pressure - psia | 34.2 | 34.1 | 34.4 | 34.6 | 33.2 | 33.5 | 35.2 | 34.9 | 34.0 | 33.8 |
| 19. | Flow Circulating Gas - CFM/Fan | 50 | 55 | 53 | 49 | 74 | 53 | 64 | 50 | 47 | 44 |
| 20. | $\Delta$ P Circulating Gas Fan " $H_2O$ | 0.95 | 0.53 | 0.56 | 0.55 | 0.51 | 0.54 | 0.54 | 0.54 | 0.43 | 0.43 |
| 21. | $\Delta$ P Across Heat Exchanger " $H_2O$ | 0.21 | 0.08 | 0.08 | 0.08 | 0.07 | 0.08 | 0.08 | 0.08 | 0.05 | 0.06 |
| 22. | $\Delta$ P Heat Exchanger and Return Passage " $H_2O$ | 0.18 | 0.11 | 0.11 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 | 0.06 | 0.08 |
| 23. | Plate Fin Center Temperature - ° F Max/Min | 193/187 | 193.5/188.5 | 196/190.5 | 193/187 | 189.5/179 | 189/182.5 | 187/176 | 183/172.5 | 188.5/179.5 | 192/184 |
| 24. | Plate Fin Exit Temperature - ° F Max/Min | 198.5/194.5 | 197.5/194 | 200/196 | 198.5/194.5 | 196/191 | 197.5/193 | 199/190 | 195.5/188.5 | 197/192 | 198.5/194 |
| 25. | Average Plate Fin $\Delta$T - ° F | 6.94 | 5.35 | 5.6 | 7.4 | 10.3 | 9.6 | 14.6 | 15.2 | 11.4 | 9.2 |
| 26. | $\Delta$ T Across Active Area - ° F | 2.5 | 2.5 | 3.75 | 3.5 | 4.25 | 4.25 | 7.0 | 7.5 | 4.5 | 3.75 |
| 27. | $\Delta$ T From Plate Centerline to Fin Exit | 4.75 | 4.5 | 5.5 | 4.5 | 5.0 | 5.5 | 9.5 | 7.2 | 4.25 | 3.5 |

TABLE II

| Cell Number | Cathode Material | Anode Material | Anode Catalyst* | Asbestos Thickness | Cell KOH (ml) | Membrane KOH (ml) | Number Support Plaques |
|---|---|---|---|---|---|---|---|
| 31 | AC # 15 Ag | Clevite No. 1 | 30-30 | 0.030" | 15.5 | 15.0 | 2 |
| 32 | AC # 15 Ag | Clevite No. 1 | 30-30 | 0.030" | 15.5 | 11.5 | 1 |
| 34 | AC # 15 Ag | Clevite No. 2 | 30-30 | 0.030" | 15.5 | 12.0 | 1 |
| 35 | AC # 15 Ag | AC 464 | 30-30 | 0.030" | 15.5 | 12.0 | 2 |
| 36 | AC # 15 Ag | Clevite No. 2 | 30-30 | 0.030" | 15.5 | 11.5 | 2 |
| 37 | AC # 15 Ag | AC 464 | 30-30 | 0.030" | 15.5 | 11.5 | 1 |
| 38 | AC # 15 Ag | AC 564 | 30-30 | 0.030" | 15.5 | 11.5 | 1 |
| 39 | AC # 15 Ag | Clevite No. 2 | 20-20 | 0.030" | 15.5 | 11.5 | 1 |
| 40 | AC # 15 Ag | Clevite No. 2 | 30-30 | 0.020" | 13.0 | 9.0 | 1 |
| 41 | AC # 15 Ag | AC 464 | 30-30 | 0.030" | 15.5 | 11.5 | 1 |
| 42 | AC # 15 Ag | Clevite No. 1 | 30-30** | 0.030" | 15.5 | 11.5 | 1 |
| 44 | AC # 15 Ag | Clevite No. 1 | 30-30** | 0.030" | 15.5 | 11.5 | 1 |
| 45 | AC # 15 Ag | Clevite No. 1 | 30-30** | 0.030" | 15.5 | 11.5 | 1 |

* 30-30 denotes 30 $mg/in^2$ Platinum - 30 $mg/in^2$ Palladium

** 20-20 anode electrode converted to 30-30 catalyst density

TABLE III

| Cell Number | Initial Performance - Volts Hours | O/C | 50 ASF | 100 ASF | 200 ASF | Final Performance - Volts Hours | O/C | 50 ASF | 100 ASF | 200 ASF | Test Duration |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 30 | 1.08 | .955 | .905 | .81 | 59 | 1.08 | .965 | .905 | .80 | 59.4 |
| 32 | 17 | 1.07 | .955 | .887 | .77 | 50 | 1.07 | .95 | .875 | .73 | 50 |
| 34 | 5 | 1.09 | .965 | .90 | .797 | 40 | 1.09 | .964 | .894 | .78 | 70 |
| 35 | 34 | 1.07 | .96 | .90 | .78 | 70 | 1.07 | .96 | .90 | .78 | 75 |
| 36 | 5 | 1.08 | .955 | .904 | .806 | 206 | 1.08 | .944 | .878 | .757 | 240 |
| 37 | 5 | 1.06 | .965 | .911 | .81 | 50 | 1.09 | .966 | .91 | .80 | 72 |
| 38 | 5 | ---- | .953 | .891 | .771 | 218 | 1.07 | .954 | .887 | .759 | 218 |
| 39 | 5 | 1.05 | .95 | .895 | .796 | 46 | 1.045 | .955 | .895 | .78 | 61 |
| 40 | 6 | 1.05 | .96 | .915 | .81 | 100 | 1.04 | .946 | .906 | .826 | 200 |
| 41 | 5 | 1.087 | .97 | .898 | .775 | | | | | | 15 |
| 42 | 5 | 1.075 | .95 | .885 | .788 | | | | | | 29.5 |
| 44 | | | | | | | | | | | 4.3 |
| 45 | 5 | 1.07 | .952 | .89 | .755 | | | | | | 24.4 |

NOTES:

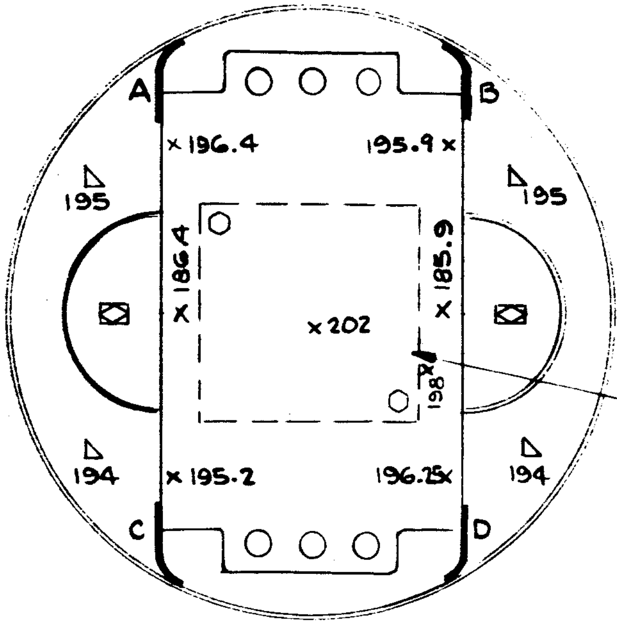
Cell 41 - Test terminated due to cavity leak.

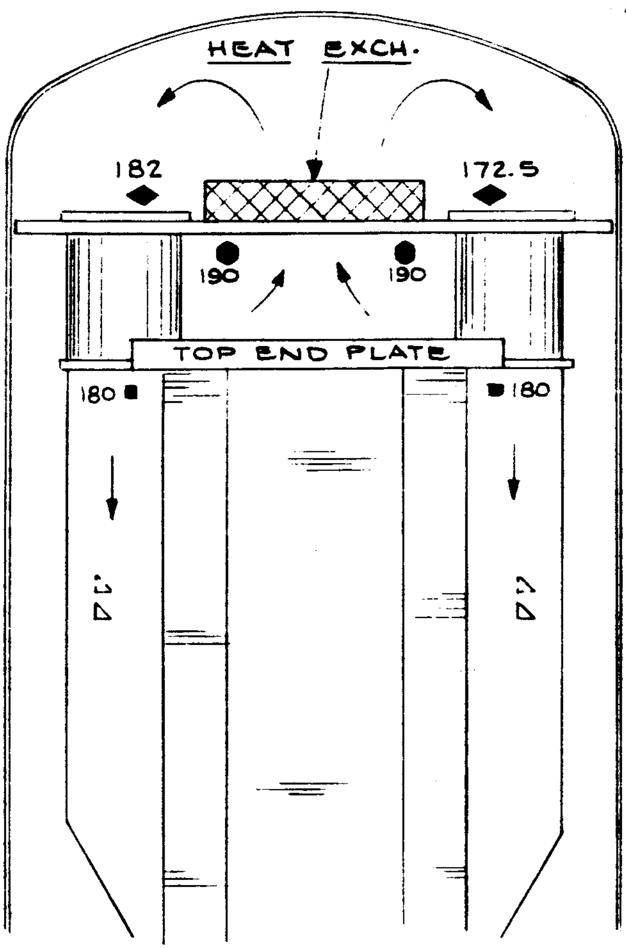
Cell 42 - Test terminated due to cross leak.

Cell 44 - Test terminated due to rapid drop in performance

Cell 45 - Test terminated due to cavity leak.

# SCHEMATIC OF 1.5KW BREADBOARD THERMAL INSTRUMENTATION & RESULTS OF A TYPICAL TEST RUN (#132)




KEY:

X OXYGEN PLATE LOCATIONS

△ SECONDARY COOLANT RETURN PASSAGE

○ SECONDARY COOLANT BEFORE HEAT EXCH.

◇ □ SECONDARY COOLANT INLET DUCT.

TEMPERATURES IN °F

FIGURE 1

# LOCATION OF PRESSURE INSTRUMENTATION

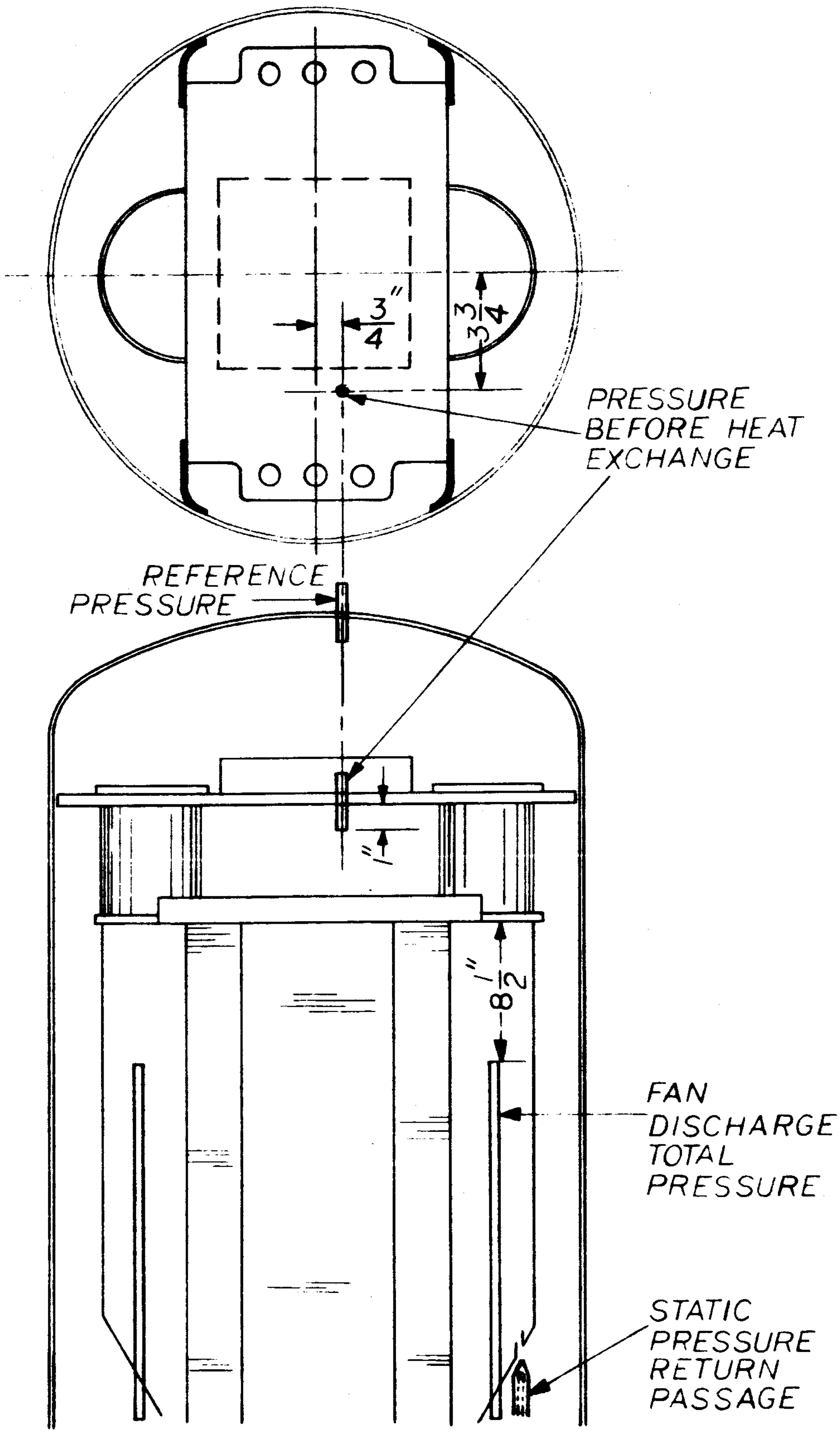



FIGURE 2

1.5 KW Breadboard
Performance Profile

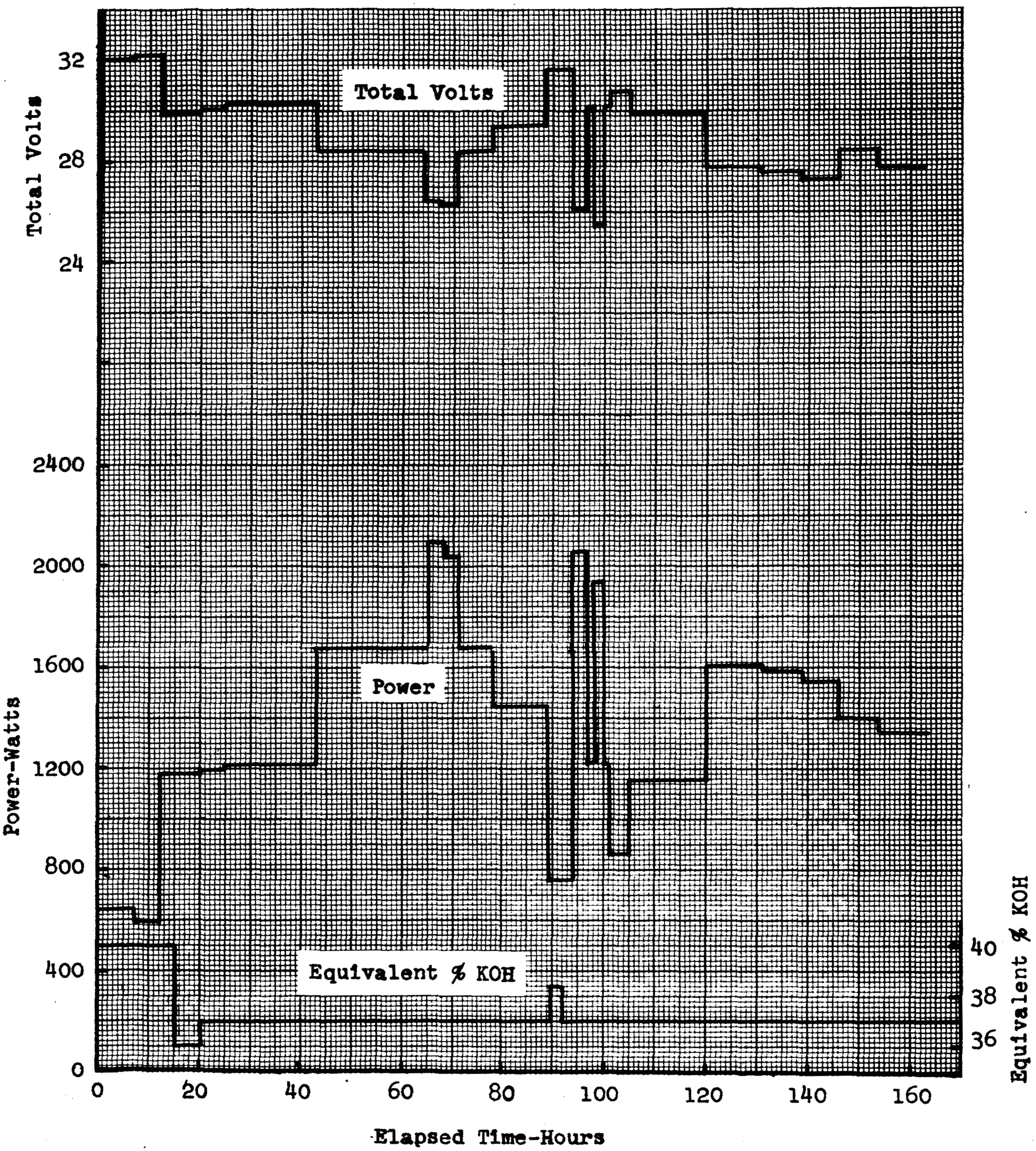



Figure 3

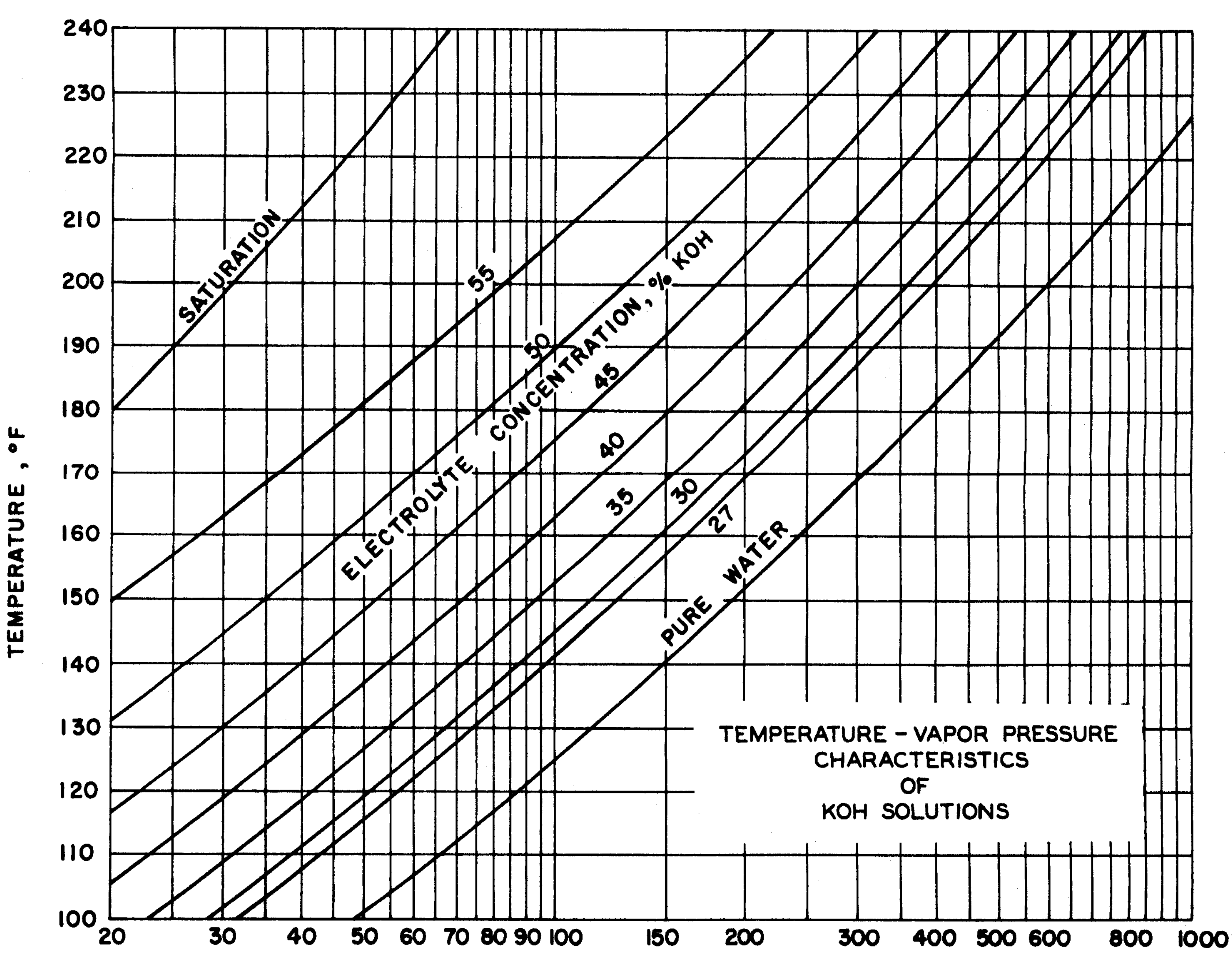

TEMPERATURE - VAPOR PRESSURE
CHARACTERISTICS
OF
KOH SOLUTIONS
SATURATION
ELECTROLYTE CONCENTRATION, % KOH
55
50
45
40
35
30
27
PURE WATER
TEMPERATURE, °F
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
VAPOR PRESSURE, mm Hg
20
30
40
50
60
70
80
90
100
150
200
300
400
500
600
800
1000

FIGURE 4

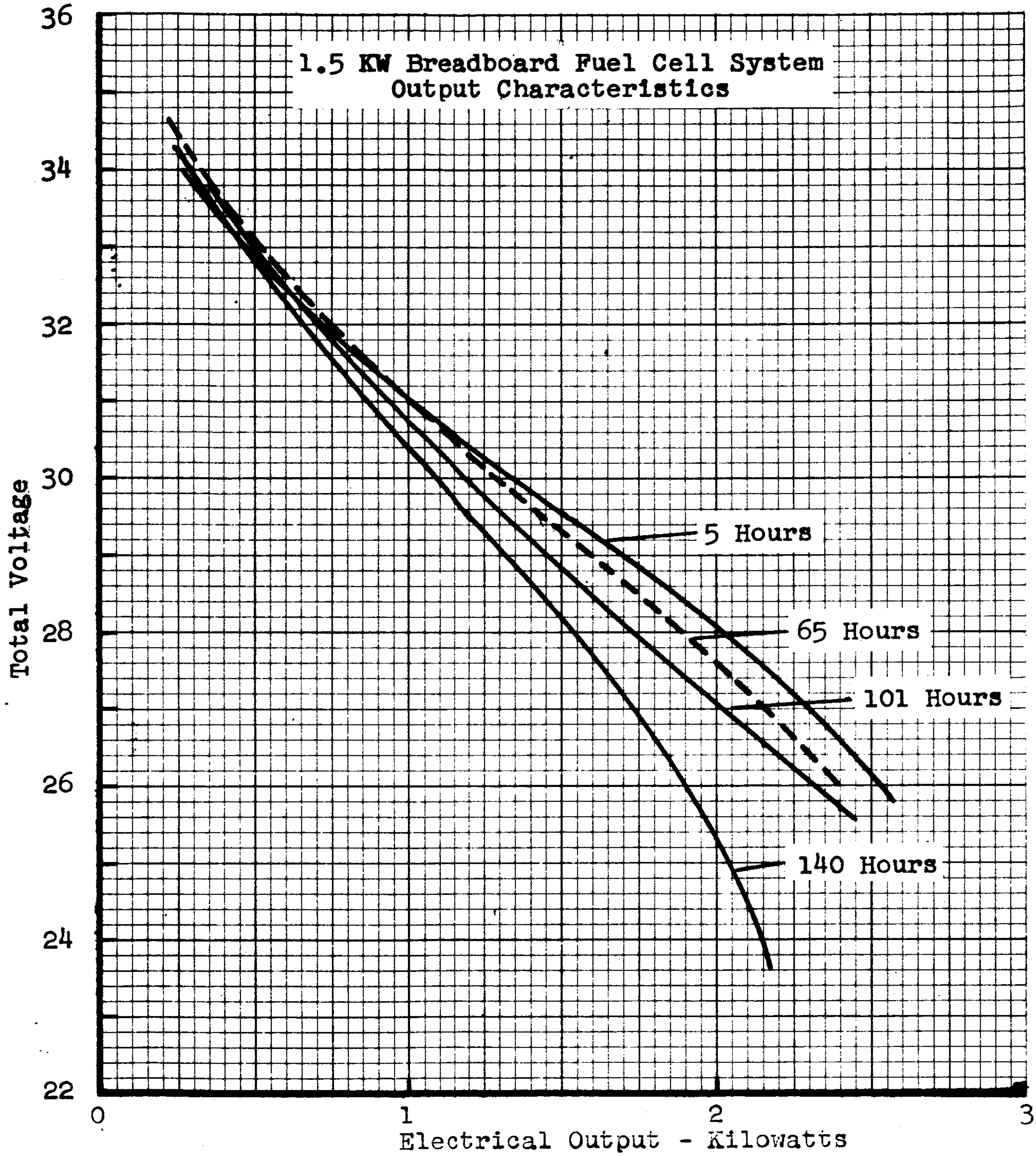
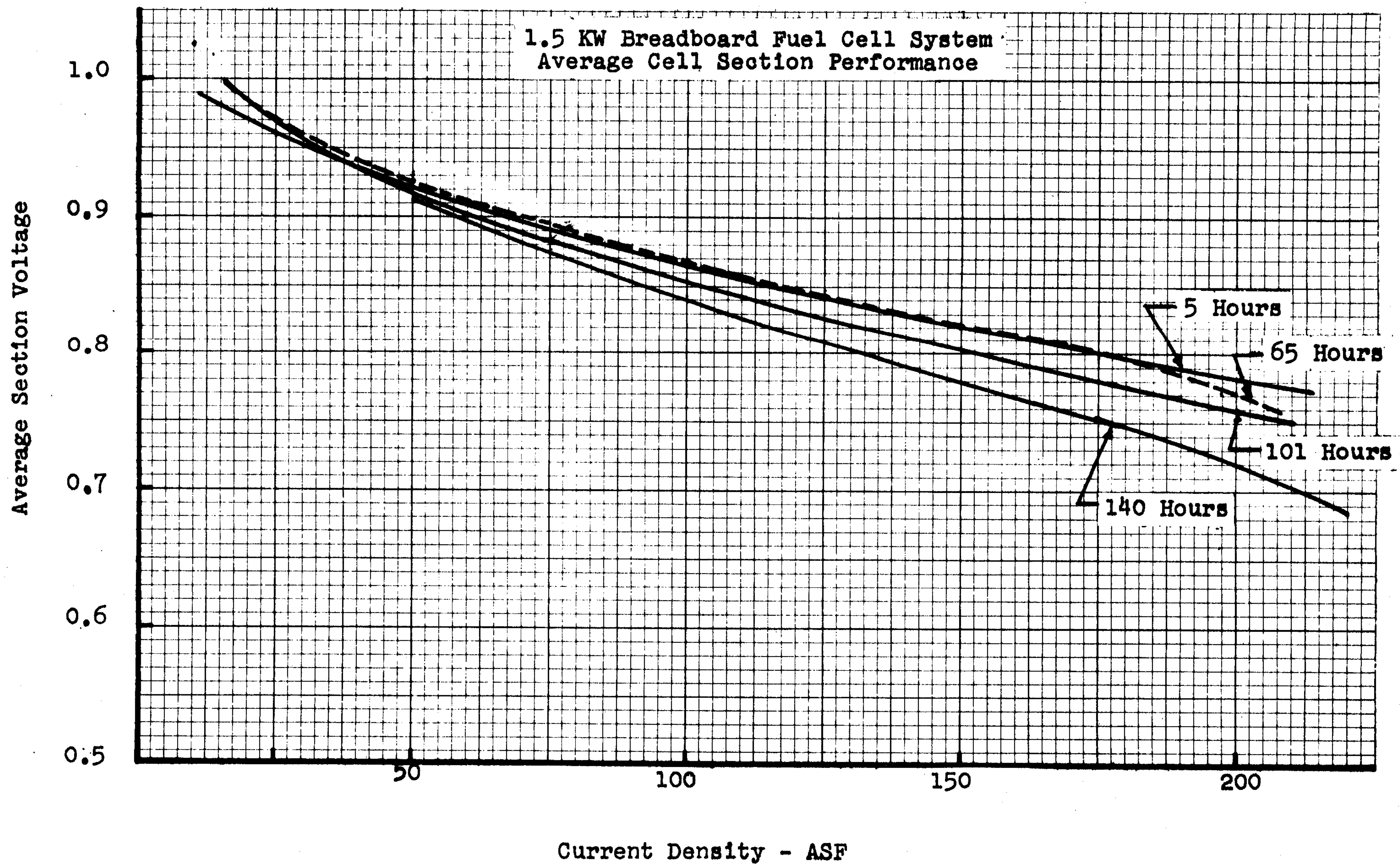

1.5 KW Breadboard Fuel Cell System
Output Characteristics
5 Hours
65 Hours
101 Hours
140 Hours
Total Voltage
36
34
32
30
28
26
24
22
0
1
2
3
Electrical Output - Kilowatts

**Figure 5**



1.5 KW Breadboard Fuel Cell System
Average Cell Section Performance
1.0
0.9
0.8
0.7
0.6
0.5
Average Section Voltage
50
100
150
200
Current Density - ASF
5 Hours
65 Hours
101 Hours
140 Hours


FIGURE 6

A-C FUEL CELL PERFORMANCE

TWO CELLS IN PARALLEL VOLTAGE VS
CURRENT DENSITY 190°F, 22 PSIG

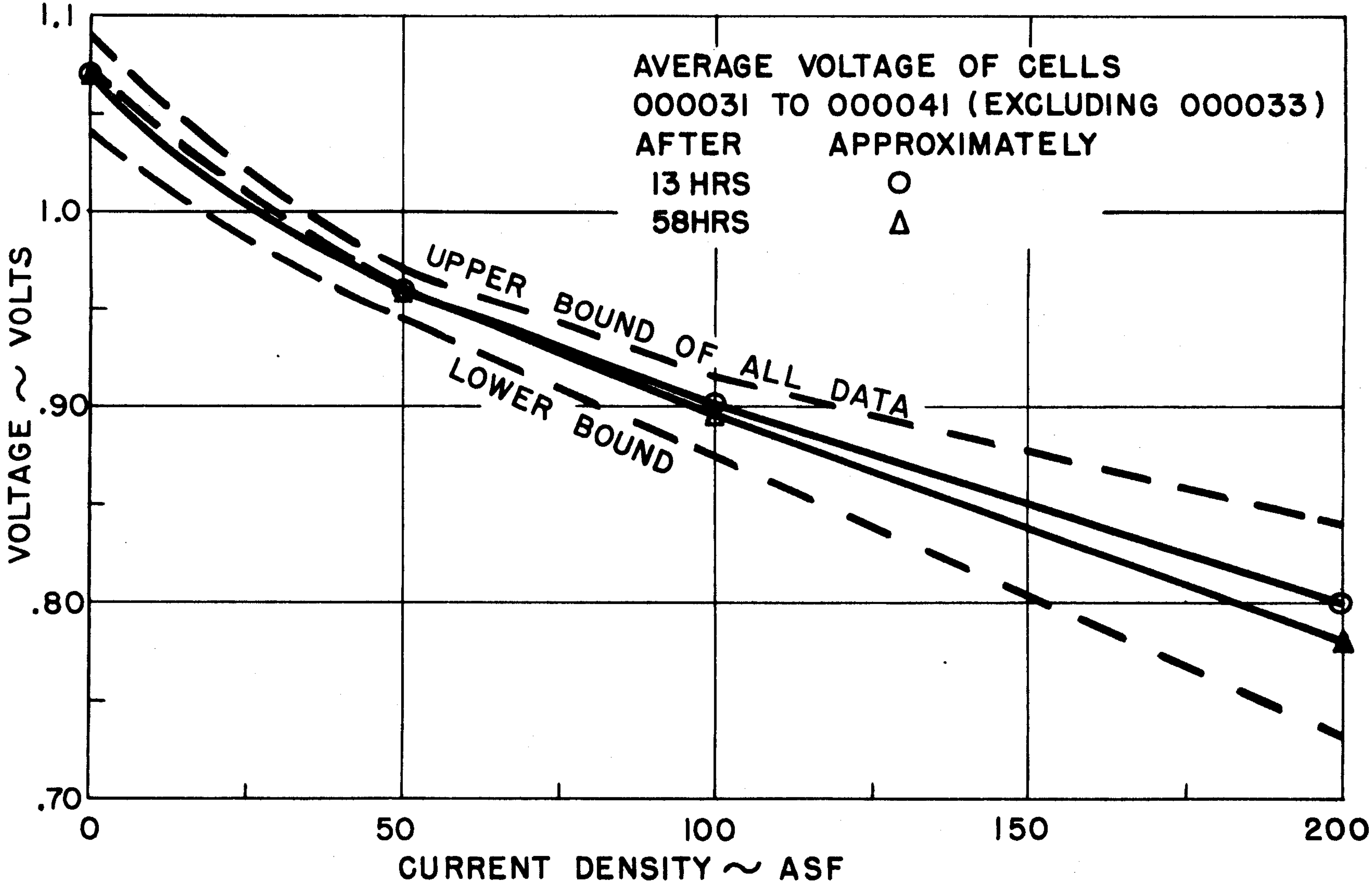



FIGURE 7

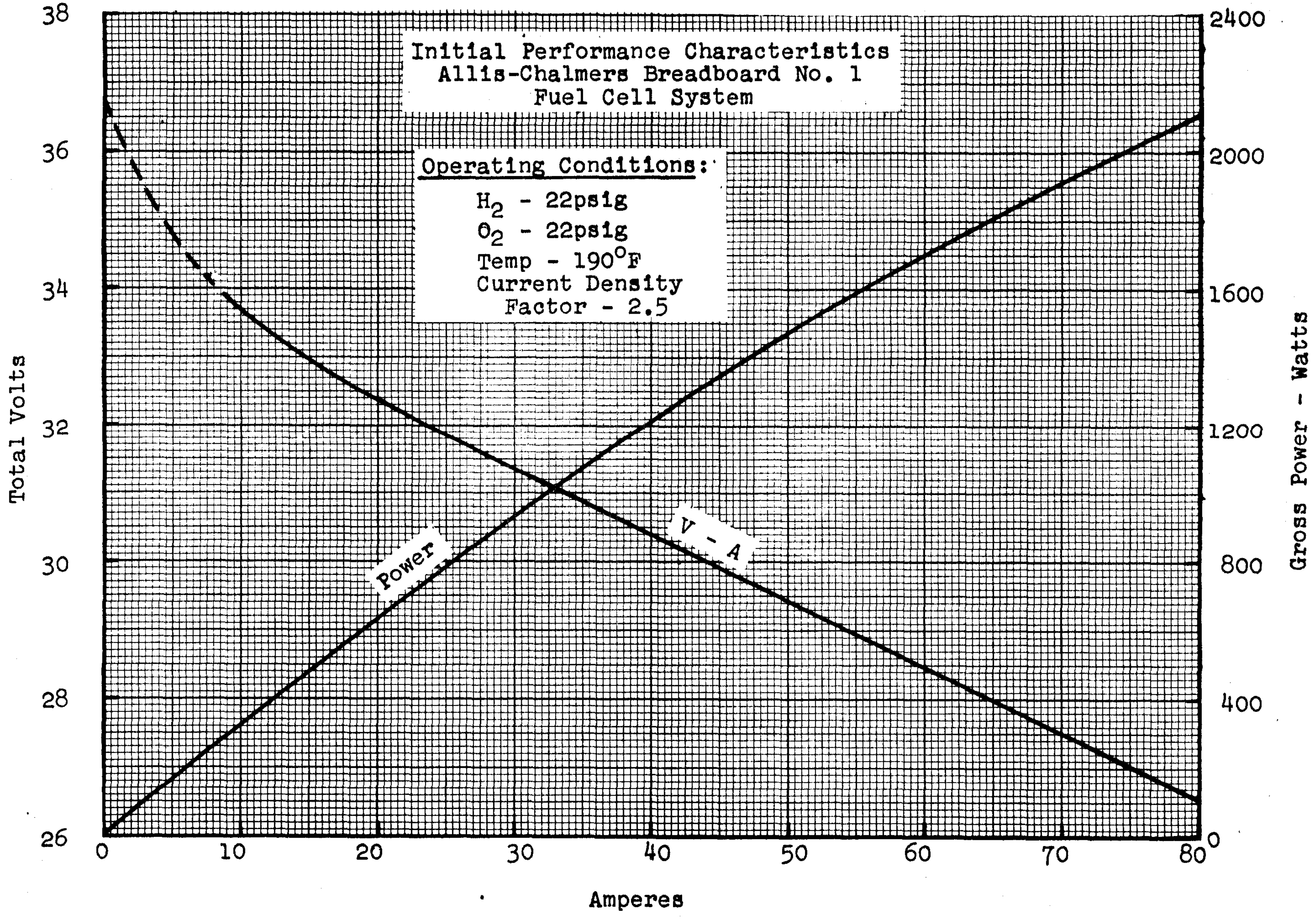

Initial Performance Characteristics
Allis-Chalmers Breadboard No. 1
Fuel Cell System
Operating Conditions:
$H_2$ - 22psig
$O_2$ - 22psig
Temp - 190°F
Current Density
Factor - 2.5
Power
V - A
Total Volts
38
36
34
32
30
28
26
Gross Power - Watts
2400
2000
1600
1200
800
400
0
0
10
20
30
40
50
60
70
80
Amperes

Figure 8

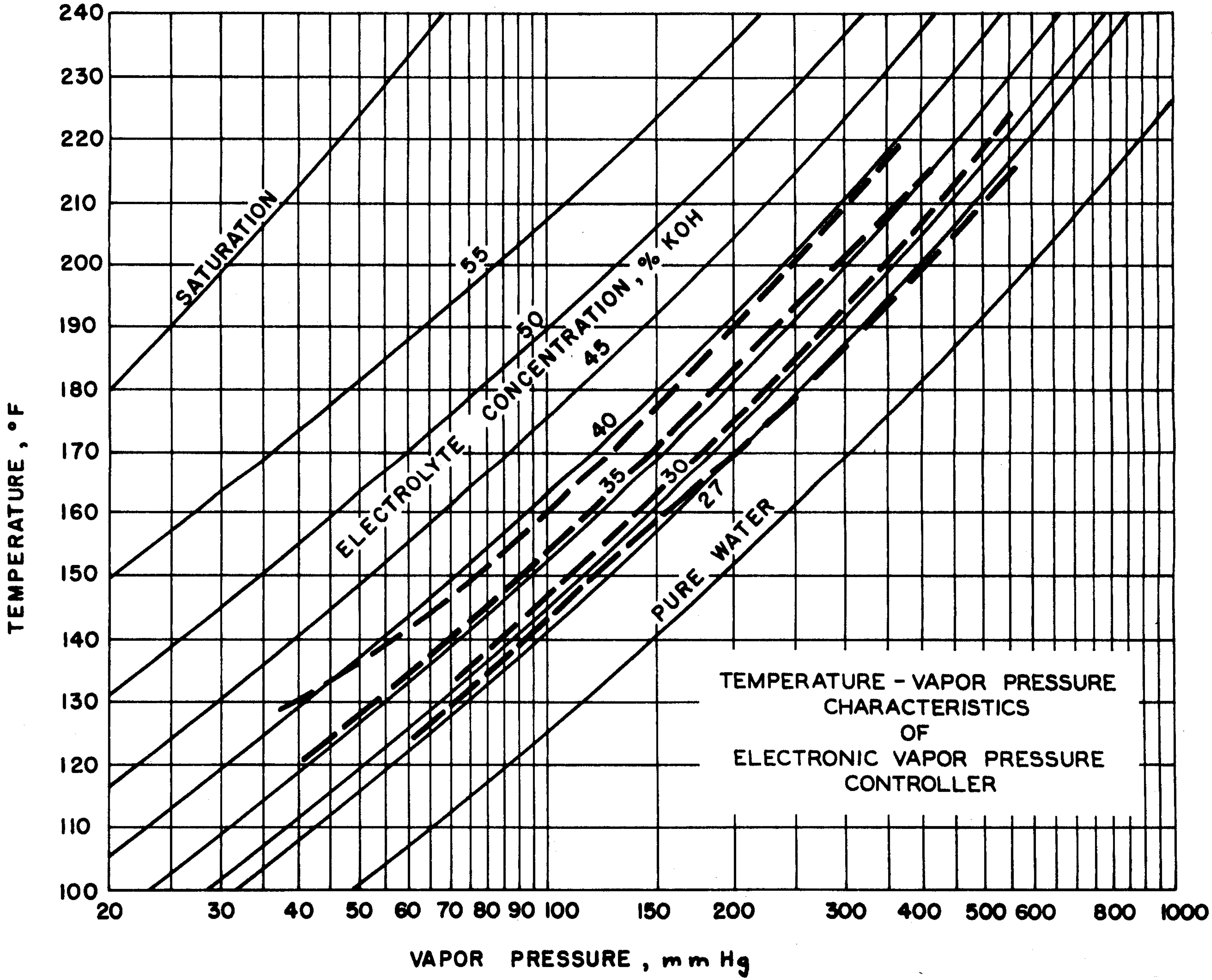

TEMPERATURE - VAPOR PRESSURE
CHARACTERISTICS
OF
ELECTRONIC VAPOR PRESSURE
CONTROLLER
SATURATION
ELECTROLYTE CONCENTRATION, % KOH
55
50
45
40
35
30
27
PURE WATER
TEMPERATURE, °F
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
20
30
40
50
60
70
80
90
100
150
200
300
400
500
600
800
1000
VAPOR PRESSURE, mm Hg

FIGURE 9